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# Flood History and River Flow Variability Recorded in Tree Rings on the Dhur River, Bhutan

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## Abstract

During the 2018 WorldDendro fieldweek in Bhutan, we examined the flood history of the Dhur River. Most villages are located along streams, so knowing the flood history of the area will enable managers to prepare for future events. We collected scarred partial cross sections from 29 trees along a two km stretch of the Dhur River, and two cores per tree from 29 other trees from six species (*Populus ciliata, Picea spinulosa, Tsuga dumosa, Quercus semecarpifolia, Pinus wallichiana,* and *Rhododendron arboreum*). We identified large flood events in 2009, 1989, and 1967 from at least two trees with flood scars or traumatic rings. Our flood-scar chronology extends to 1940 with five cross-sectioned trees, and back to 1904 with core evidence from two trees. The oldest flood scar occurred in 1967. The 2009 flood scar was recorded in most of our streamside samples and is the result of heavy precipitation from Cyclone Aila at the end of May 2009. Two other storms and proceeding flood events occurred in 1989 and 1967 according to additional scars detected in several samples. This work demonstrates the successful use of density fluctuations in *Pinus* along with scarring in multiple species to reconstruct past flood events and identifies the effects of Cyclone Aila, as an extreme event for this area, which was unprecedented for the past hundred years.

**Keywords:** Flood scars; Dendroecology; Flood history; Dendrochronology; Bhutan

## Introduction

Water resources are an important component of the economic sector of Bhutan as well as for daily usage by the Bhutanese people (FAO 2018). The generation and sale of hydropower to India is approaching 50% of the Gross Domestic Product for the country, but many regions suffer from irregular water supply, which includes dry streams for some part of the year and heavy floods during the monsoon season (FAO 2018). Dendroecology has already been applied in Bhutan

(Dukpa *et al.* 2018), but research into flood events through dendrochronologically dated flood scars has never been used in this country till now and this work seeks to demonstrate the value of crossdated flood histories to inform local water resource managers. Dendrochronology can be used to date flood scars on the upstream side of trees that are caused by suspended debris in large flood events (Ballesteros-Canova *et al.* 2015). By the position and date of these scars, past flood intensity can be reconstructed, providing historical flood information for watershed managers. Stakeholders and government leaders in Bhutan share a great concern for water management as demonstrated by the Bhutan Water Policy (2007) which "recognizes that water is a precious natural resource that is basic to all social, economic and environmental well-being and, as such, the water resources need to be conserved and managed efficiently, while ensuring sustainability and without damaging the integrity of the environment" (FAO 2018).

McCord (1990) first demonstrated the extensive use of flood scars to understand the flood history in multiple mid-to-high elevation watersheds in the southwestern United States. His techniques have been followed in this paper to reconstruct past flood events. He sampled 20 separate watersheds with only 1-5 samples per watershed. He mainly used cores to sample obvious scars from trees close to the stream channel and documented that this was sufficient to records most major events along the stream channel. McCord (1990) only collected three crossections but noted that they were extremely helpful in determining the flood event dates, especially on multiply scarred trees.

Ballesteros *et al.* (2011) estimated flash flood occurrence in an unmonitored stream in Spain by using the flood scars on trees as an indicator of past flood height. From these flood scars, Ballesteros *et al.* (2011) were able to estimate past discharge during flood events so that watershed managers can understand how these streams have behaved in the past to plan for future events.

Ballesteros *et al.* (2015a) reviewed many tree-ring flood studies finding 47 papers on the topic with 56% of the work coming from the United States and 36% of the work coming from Europe. This demonstrates that very little research is done on flood scar events in other parts of the world. They didn't find any published paleoflood records from tree rings in Asia. From the studies that they found throughout mostly North America and Europe, broadleaved trees represent 60% of the research, with only 40% of the studies dealing with conifers. They show that a variety of indicators are used to identify flood events including scars, tree tilting, and wood anatomical characteristics. Conifers have been shown to have a decreased ring width, reduction in earlywood tracheid size (Ballesteros-Cánovas *et al.* 2010, Arbellay *et al.* 2012a, 2012b), and production of traumatic resin ducts (TRD) from mechanical damage (Stoffel 2008). In broadleaf trees the most common response is a decrease in vessel area during flood conditions producing a distinctive "flood ring" (St. George *et al.* 2002, Ballesteros-Cánovas *et al.* 2015).

At the end of May 2009, Bhutan was struck by Cyclone Aila, which produced a large amount of precipitation and flash floods throughout central Bhutan. This event was recorded as one of the worst rainfall and flood events in the history of Bhutan (Koike and Takenaka 2012). Our objective was to record the discharge of that event and estimate prior flood frequency. We compared the 2009 flood scars with past flood scars recorded in the sampled trees to see if, in the recent past, there were any similar size storms and flood events.

## Methods

### Field Methods

In June 2018, we were invited to do research in Bhutan through the auspices of the 10th WorldDendro fieldweek hosted by the Ugyen Wangchuck Institute for Conservation and Environment Research (UWICER) in the Bumthang province of central Bhutan. Our group chose to attempt a flood reconstruction of the Dhur Chu (river) through flood scars.

After reconnaissance, we selected a two km stretch of the Dhur River (Figure 1) along which we collected partial cross sections from 29 trees (only wedges, no trees were felled) and cores from another 29 trees. We sampled six species (*Populus ciliata*, *Picea spinulosa*, *Tsuga dumosa*, *Quercus semecarpifolia*, *Pinus wallichiana*, and *Rhododendron arboreum*) along the river to determine their capacity for crossdating and preservation of flood scars.

Following McCord (1990), we thought that we could obtain a good record of past flood eveents from multiple scarred trees along the stream channel. We collected the maximum sample size that was recommended by McCord (1990) as most of his samples were from 1-5 trees per watershed and his maximum was 30 trees in one location. We also favored partial crossections from living trees to get a good record of past scars where McCord (1990) mainly used increment cores with just a few crossections. Along the two km stretch of the south shore of the river, we took partial cross sections from every clearly scarred tree and others that showed surface growth sutures that suggested a buried scar. We worked with a crew of two local loggers to cut these partial sections (Arno and Sneck 1971, Speer 2010). From nearby unscarred trees we took two cores per tree at breast height to construct a dating chronology from a minimum of ten trees per species when species density allowed this. We also sampled seven trees on an adjacent terrace to determine their establishment age on the terrace. We stored the cores in plastic straws that we sealed at the ends with staples. Site, trees, and core identification codes were written on the straws along with all notable tree-specific or site-specific details. This information was later transferred to the core mount. Field identification of tree species was further checked in the laboratory using coarse wood anatomy characteristics for genus identification.

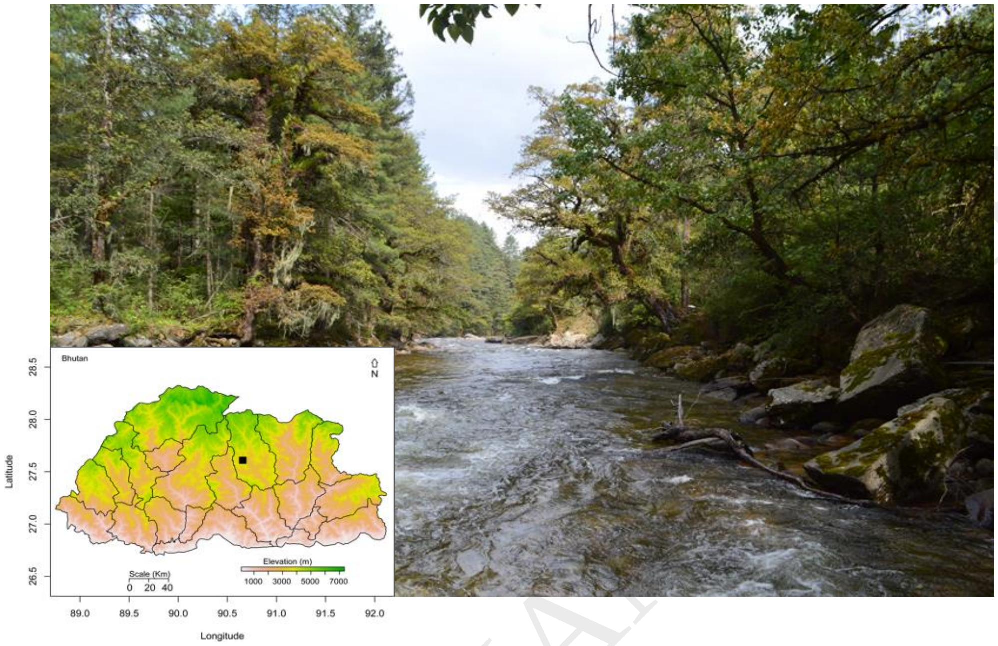


Figure 1: Location and photo of Dhur River in Bumthang province of central Bhutan (photo by Matt Bekker).

The 2009 flood-level discharge on the Dhur River was estimated at the location of one of our 2009 flood-scarred trees. To estimate the flood-level discharge, we first measured the width of the current river defined by the distance, from shore to shore, along the surface of the water. We extended a rope from the 2009 flood scar and tied it tight at the height of the scar. We used the distance from the water surface to the rope to make sure that the rope was level. Then we took depth measurements from the stream bottom every meter along the rope to the current stream height and to the height of the 2009 flood-scar. We also measured the distance from the trees where we tied the rope to the bank at the same height, then calculated the stream cross section area from these measurements. We estimated flow speed from timing leaves as they floated downstream (we realize this is a coarse measurement of stream velocity, but it is what we had available at the time and is similar to the float method described by Michaud and Wierenga 2005). For the 2009 Cyclone Aila stream flow, we multiplied the flow rate six times based on USGS data for low and high stream flows as a conservative estimate (USGS 2018). This is also within the range of the velocity from a Glacial Lake Outburst Flood (GLOF) event from the Mo Chu in 2015 although the subsequent discharge was three times as great from the GLOF event as our calculated discharge from Cyclone Aila (Gurung *et al.* 2017).

Discharge can be calculated given the cross sectional area of the stream and the velocity using the following equation (Equation 1, Michaud and Wierenga 2005).

$$Q = AV \qquad \text{(Equation 1)}$$

Where Q is discharge, A is the cross sectional area of the stream at one location, and V is the velocity of the stream.

**Laboratory Methods**

Due to the abbreviated time for analysis time during a seven-day fieldweek, we could not completely dry our samples, but we did put the cross sections into a drying oven for 24 hours to try to reduce their moisture level for better surface preparation. We mounted the cores while they were still wet on prefabricated wooden core mounts, with the cross-sectional view facing up. We used Elmer's white glue with string or tape to hold the cores in place while they dried for approximately 12 hours.

We worked with a local sawmill to plane the cross sections and remove the rough chainsaw cuts. Then we sanded all samples with progressively finer grits of sand paper using 80, 240, 320, and

400 grit sand paper. On the surface of those cross sections with flood scars, the areas around the scars received an additional sanding with 30 micron sanding film to enhance detection of wood anatomical reactions to wounding that might otherwise go unnoticed. After all cross sections and cores were sanded, the last ring in each sample was preliminarily dated to 2018 with a few cells developed from our early June sampling although some species (like *Quercus*) had not developed any cells yet for 2018. We then skeleton plotted 10 samples from each species to build a local master chronology and dated the rest of the samples using the memorization method (Douglass 1941, Speer 2010). We measured the samples to 0.001 mm using a Velmex Measuring System and MeasureJ2X software. The dating was checked in COFECHA (Holmes 1983) and with frequent returns back to the wood samples to check any dating discrepancies that were identified by the program. Final chronologies were built from the well-dated samples using age–dependent splines (Melvin and Briffa 2008) with the signal free standardization technique in computer program RCSigFree (RCSigFree 2018). The signal-free technique improves the preservation of low frequency in tree-ring chronologies (Cook *et al.* 1995). We plotted flood scars and other injuries using the FHAES 2.0.2 software (Brewer *et al.* 2017, Sutherland *et al.* 2017). A clear scar with wound wood and a healing curl was designated as a scar while other injuries such as traumatic resin ducts or other cell reactions in a ring were noted just as injuries. If injuries lined up with other clear scars, they counted as supporting evidence of a flood event.

Integrated Water Vapor Transport (IVT) data was collected from NOAA Earth System Research Laboratory's NCEP/NCAR Reanalysis portal for derived meteorological variables (NCEP 2018) and compared to storm track data came from the IBTrACS v03 revision 6 (IBTrACS 2018). IVT is a combination of measuring atmospheric water vapor and wind direction (kg/m/s) and is an accurate variables to display storm origination in the oceans prior to precipitation and landfall.

IVT combined with the storm track data validates each other of the trajectory and intensity of the storm event. We examined the pressure fields for the preceding winter and spring season for each of our events that scarred at least two trees and found significant storms for each of our events making landfall and reaching the Bhutanese Himalaya.

## Results

We developed three chronologies from *Tsuga dumosa* (20 series, series intercorrelation 0.524, mean sensitivity 0.183, flags 5), *Pinus wallichiana* (10 series, series intercorrelation 0.514, mean sensitivity 0.245, flags 1), and *Populus ciliata* (12 series, series intecorrelation 0.407, mean sensitivity 0.277, flags 5). We also collected 10 cross sections from *Quercus semecarpifolia*, which did not crossdate and had poor ring boundary differentiation. We ring counted these samples and consistently found the 2009 flood scar, but did not feel confident about crossdating prior to that event. We also collected one *Rhododendron arboreum*, which was also ring-counted, and showed a 2009 scar. The *Quercus* went back to approximately 1940 and the *Rhododendron* went back to 1932 based on our ring counts.

All samples were collected during two days in the beginning of June. By this time we found that *Quercus* and *Rhododendron* had not yet produced any earlywood vessels. *Populus ciliata* and *Picea spinulosa* had produced just a few earlywood cells, *Tsuga dumosa* produced about 10 earlywood cells, and *Pinus wallichiana* had produced over 20 earlywood cells. This suggests that the pine trees in this region either start to grow earlier than the other species or it grows faster than the other species. This information was used to calibrate our determinations of when in the growing season a scarring event occurred, based on the proportion of cells that have developed at the time of each injury. The flood scars all occurred early in the growing season with most of the conifer samples recording an Early-Earlywood scar and the oak and rhododendron recording dormant season scars.

The scars occurred an average of 118.5 cm (stdev = 152.9 cm) from the edge of the current stream channel and the bottom of the scar was on average 86.5 cm above the current stream channel (stdev = 33.9 cm). The scars were on average 31.2 cm from bottom to top of the scar along the stem (stdev = 28.7 cm). These numbers demonstrate how far the floodwaters were above and outside the current stream channel. At the time of our sampling the stream discharge is estimated at 17.04 $m^3/s$ (Figure 2). Using a conservative estimate for the velocity of the stream during Cyclone Aila, we calculate a flow of 543.53 $m^3/s$, which is about 32 times larger than that which occurred on the day of our measurements. Most of the sampled trees on the terrace established between 1958 and 1963, which predated our recorded flood events. This could be from an un-recorded flood or even road construction which was up-slope and not far from our sampling site. The other trees were older and probably represent natural regeneration over time rather than a pulse of establishment after a flood event.

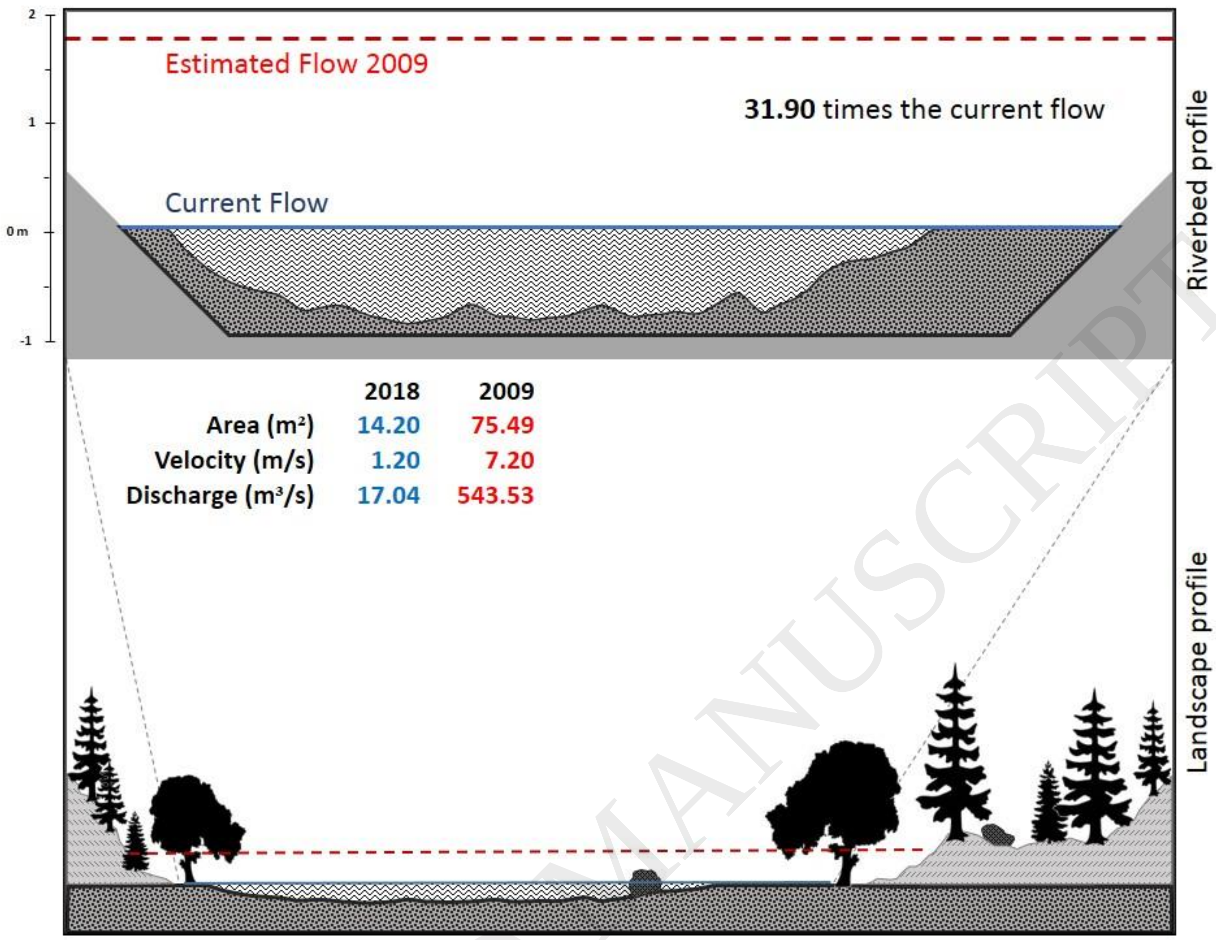


Figure 2: Diagram of the stream channel where we measured stream area for the purpose of discharge calculations. We calculated discharge for the current flow (2018) as well as the 2009 flood event where we had scarred trees (sketch by Arturo Pacheco).

We documented the occurrence of each scar along with density fluctuations within the ring (for *Picea spinulosa* Figure 3) and traumatic resin ducts (for *Tsuga dumosa* Figure 4) to create a flood history chart (Figure 5). *Picea spinulosa* consistently recorded a distinctive false ring or density fluctuation in the middle of the earlywood associated with flood events (5 crossections sampled for flooding). We had fewer samples of *Tsuga dumosa* (1 crossection sampled for flooding), but it showed traumatic resin ducts occurring in the years of injury. All five species recorded scars and

91% of the samples recorded the 2009 event from Cyclone Aila. We only had two trees recording two other events in 1989 and 1967, which were also related to documented storms in the region.

Figure 3: Density fluctuation in the middle of the 2009 ring of *Pinus wallichiana* from Cyclone Aila.

Figure 4: Sampled tree on the downstream site with a large flood scar (A). Traumatic resin ducts in *Tsuga dumosa* from the 1989 event (B).

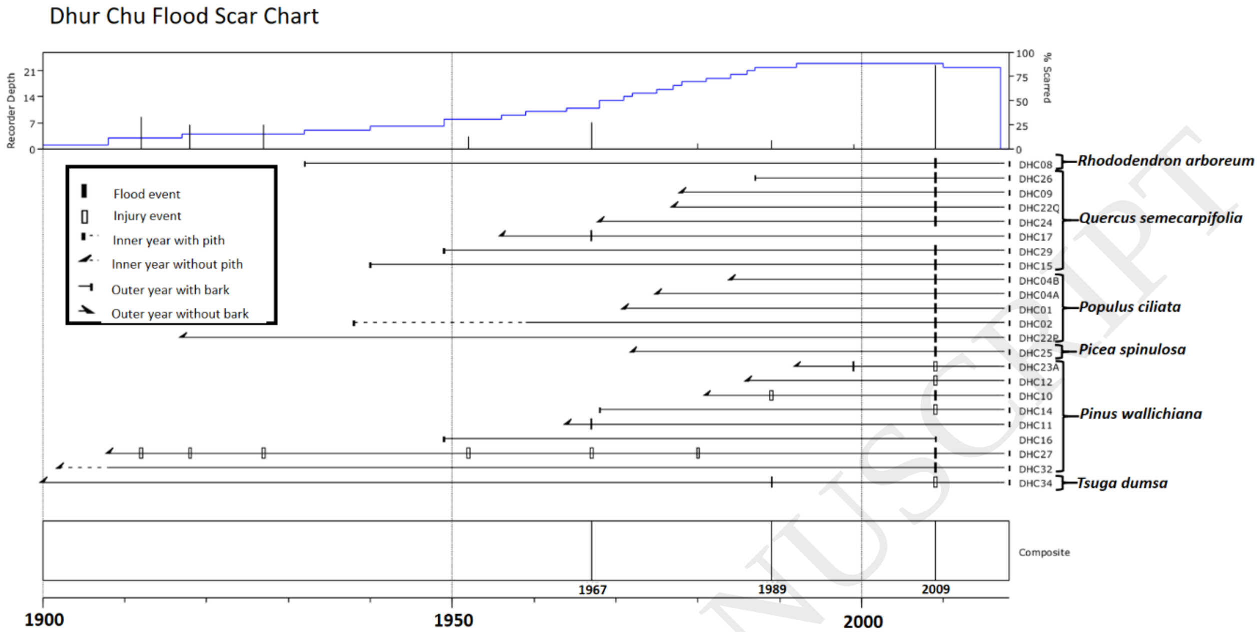


Figure 5: Flood scar chart that shows the innermost date of the samples and the outside date. The solid lines are scars that we believe are due to flooding based on their position on the stem facing upstream. The open rectangles are other evidence of damage such as a density fluctuation or traumatic resin ducts. An event was only considered a flood scar if it was observed on at least two trees and then it appears in the composite chronology along the bottom of the graph (plotted in FHAES 2.0.2).

We identified the individual storms that likely caused our scars from the Integrated Water Vapor Transport data and the storm track data. These storms occurred in the proceeding winter to spring (January to May) and stood out from the background level of storm activity (Figure 6). Two of these were category 1 tropical cyclones when they came to Bhutan. These were extreme events compared to the normal conditions in Bhutan and their effect is apparent in the tree-ring record.

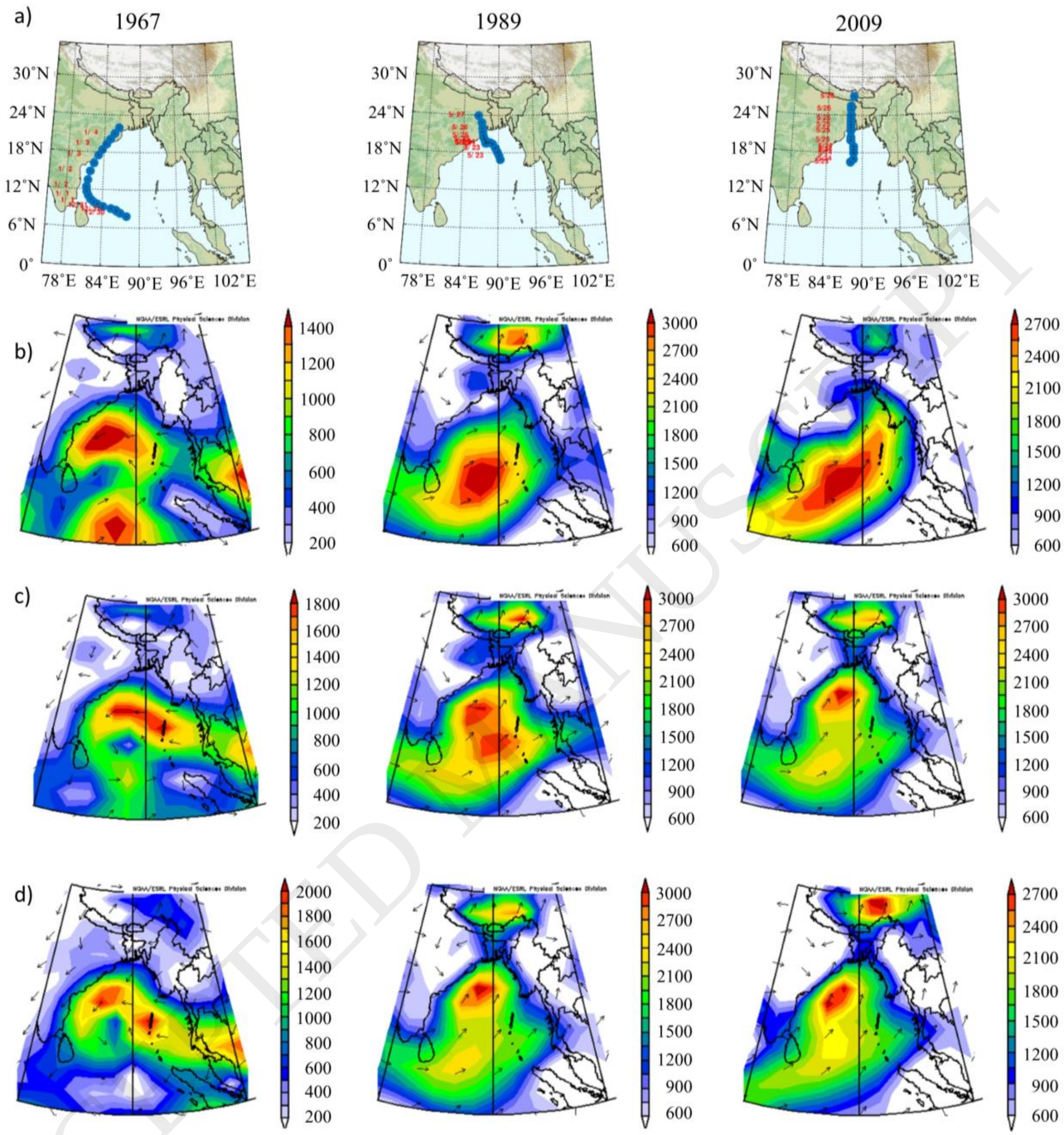


Figure 6: Storm track and Integrated Water Vapor Transport (kg/m/s) for each of the reconstructed storms (1967, 1989, 2009) from A) storm-track, B) two days prior to reaching Bhutan, C) one day prior, D) day of the storm. The storms weakened as they moved over land but they still brought heavy rain the day of the storm.

**Discussion**

All six species sampled recorded and preserved flood scars. The scars were over a meter above and about a meter outside of the current stream channel, demonstrating the size of floods that can occur from a tropical cyclone. We conducted a visual survey of the trees and sampled ones that had obvious scars or large suture zones that were likely covering a buried scar. With this approach, we sampled approximately 50% of the trees along the stream bank. Many trees seemed to be protected by other nearby trees, which might have kept them from being scarred. Flood scaring is a haphazard event and we don't expect 100% of the trees to be injured. We are also more likely to pick up the modern scars that still appear as an open wound, rather than an older scar that could be buried inside the tree. But even with this bias, it seems that the 2009 event was extreme, much larger than anything that has occurred here since 1940, the period when our scar chronology is well replicated.

All six species we sampled were scarred and retain the scar without rotting away. The *Populus* and *Quercus* trees seemed to be the most scarred, possibly because they are more likely to establish directly along the stream bank. The *Quercus* were more difficult to work with because they did not produce clear ring boundaries and subsequently did not crossdate. Consequently, we recommend the use of *Populus* because of its abundance directly along the stream. *Pinus* and *Tsuga* were also good recorders of floods because of their clear crossdating as well as their susceptibility to scarring. These latter two also have the potential to attain great ages (*Pinus wallichiana* ~ 700 years and *Tsuga dumosa* ~ 1100 years Cook *et al.* 2003, Gaire *et al.* 2013) offering the researcher an opportunity to push reconstructions further back in time.

Each species also initiates growth at different times and produce a different number of cells by the same time in the year, so one needs to be careful to understand the wood anatomy and growth timing of all of the species sampled on a site. Because we sampled all six of our species on the same day, we could be certain about the amount of growth that had occurred in the season up to the first week in June. This showed that the pine grew the quickest and the oak was the slowest to show any growth. These differences should be taken into consideration when interpreting monthly timing of events from the amount of wood production on a certain species of tree.

Ballesteros *et al.* (2015a) reviewed studies applying tree rings to floods. Most previous studies have been conducted on broadleaf trees and the most common response was a “flood ring” characterized by abnormally small mean vessel areas due to long-term root submersion (St. George *et al.* 2002). Although we were unable to conduct microscopic wood anatomy on our samples during the Fieldweek, we did notice a consistent density fluctuation, much like a false ring, in the pines (Figure 3) that, to our knowledge, has not been described in any previous study. Common responses in conifer species to floods have included scars, growth suppressions and releases, and reaction wood (Ballesteros *et al.* 2010, Ruiz-Villanueva *et al.* 2010, Ballesteros-Canovas *et al.* 2015b), but not density fluctuations or false rings. However, Ballesteros *et al.* (2010) found smaller earlywood tracheids in flood-affected *Pinus pinaster*, and Young *et al.* (1993) described frequent false rings in periodically-flooded bald cypress (*Taxodium distichum*) saplings. We encourage more research on the potential occurrence and mechanisms of false ring formation in *Pinus* associated with flooding. We expect this characteristic would be more likely to form under situations of extensive, long-term flooding that would deprive roots of oxygen rather than flash flooding that quickly drains from the landscape.

Integrated Water Vapor Transport (IVT) combines both atmospheric water vapor and wind direction to observe regional-to-mesoscale storm events dating to 1948. This combination allows for accurate measurements of storm origination in the ocean, prior to precipitation, and its landfall.

It is used commonly for distinguishing the source region and landfall trajectories of Atmospheric Rivers (ARs) for the North American Pacific Coast (Dettinger *et al.* 2011, Albano *et al.* 2017). The storm track data allowed us to investigate every major storm for the previous winter and spring for the year of the flood scar. We then used the IVT data to confirm the origin of the storm and how long it took for the water vapor to reach the Dhur River. The combination of IVT and storm track data validated one another, as well as confirming that it takes about three days for these large storms to reach our study region. Therefore, local authorities have around a three day period to warn Bhutanese civilians of upcoming catastrophic flood risks.

Cyclone Aila was an extreme event in this area. This catastrophic event defines the highest stream flow in recent history. The only other events that we can imagine would be more catastrophic would be Glacial Lake Outburst Floods (GLOF) that occur at high elevations as a consequence of rapidly accumulating glacial meltwater, such as the 1994 GLOF on the Mo River (Watanbe and Rothacher 1996, Komori *et al.* 2012, Gurung *et al.* 2017). We suggest it would be useful to conduct a similar study such as this in that area to determine the effects of GLOF events, and to study their historical occurrence.

## Conclusions

We were able to reconstruct the Cyclone Aila event in 2009 with strong representation of flood scarring in the trees. We further reconstructed two older events of lesser magnitude based on the percentage of trees scarred in 1989 and 1967. Over the past 78 years (1940-2018) Cyclone Aila was the most extreme event in this area. This could be the start of what the IPCC suggests will be a period of more frequent and severe storm events in the future (Field 2014). We identified a density fluctuation in *Pinus wallichiana* that can be used in the future, in conjunction with scarring, as a reliable recorder of flood events in pines. This work has shown strong potential for flood reconstruction in Bhutan and may lead the way to further work examining Glacial Lake Outburst Flood events.

Declarations of interest: none

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